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THE INFLUENCE OF REFLECTIONS ON THE SOUND-PRESSURE SPECTRA OF JETS

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THE INFLUENCE OF REFLECTIONS ON THE SOUND-PRESSURE SPECTRA OF JETS

by

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SUMMARY

Measurements of the sound field of turbojets, in static tests or in flight, are usually made in the presence of a ground whose acoustic characteristics are quite inadequately known or even ignored.

The sound-pressure spectra are then perturbed by complex reflection phenomena that make their application difficult. It follows from this that the free-field acoustic characteristics are difficult to establish and any attempted correlation, extrapolation or simple comparison of results becomes imprecise.

With the aim of standardizing the experimental conditions, I.S.O. recently proposed that measurement of the sound field of turbojets be made above a hard surface (concrete or the like), thereby at least ensuring fixed ground characteristics. But such an arrangement, together with a knowledge of the correction factors resulting from reflection phenomena, offers the additional advantage of permitting restitution of the free-field spectra.

SNECMA, having established a test facility for measuring turbojet noise patterned on the I.S.O. recommendation, undertook a theoretical and experimental study of these problems. The computed curves and some experimental results abstracted from this study show that the influence of these reflections is far from negligible and can be taken into account either by correcting the measurements or at the stage of estimating the noise of a turbojet.

Some applied examples confirm the correctness of the results obtained.

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1. INTRODUCTION

The laws governing the sound emission of jets are complex, and a comparison of theoretical findings and experimental results can not be made in a valid way unless their "free-field" acoustic characteristics can be measured.

Knowledge of these characteristics is indispensable in the investigation of a number of problems, such as the verification and examination of the similarity laws of acoustics, acoustic tests on silencer models and carryover of the results to the full-scale engine, establishment of noise prediction methods, etc.

Although it is relatively easy to attain free-field conditions in experimental studies on models (measurements in anechoic chambers or in the open air at a sufficient height above the ground), it is practically impossible to obviate the proximity of the ground in acoustic measurements made near turbojets. The measurements are then perturbed by reflection phenomena that profoundly alter the sound-pressure spectra.

After sketching the practical importance of these phenomena we shall describe briefly the format of the theoretical approach to the problem of reflections from a plane, non-absorbing surface and some results of an experiment conducted for the purpose of verifying the theoretical results. An overall comparison between some spectra measured around a turbojet and the corresponding computed spectra show that it is possible either to reconstruct the free-field spectra from measurements made above a reflecting ground or to make an adequate estimate of these spectra in the presence of such a ground.

2. ILLUSTRATION OF THE PRACTICAL IMPORTANCE OF THE PROBLEM

The sound field of turbojets is ordinarily measured at a large distance (50 meters or more) so as to be located in the far-field of the sound source, which ensures that the sound field will fall off inversely with distance. During these measurements it is rarely possible to find a test area having uniform, well-established characteristics. In most cases the measurements are made at the edge of an airfield runway, above a grassy ground or a mixed terrain (part grass, part concrete).

The sound-pressure spectra of jets measured under such conditions are then far from having the regular shape of the free-field spectra shown in Fig. 1 (measurements made on a turbojet mockup in an anechoic chamber). On the contrary, they exhibit a series of valleys and peaks produced by complex reflection phenomena that are strongly influenced by the nature of the ground and the location of the receiver relative to the source.

As an example, Fig. 2 shows spectra from an ATAR turbojet measured at a constant height above a grassy ground and at three distances from the engine in the direction of maximum sound emission from the jet.

In a similar vein, Fig. 3 (with the same engine) shows the spectra measured above the same test area, at a like horizontal distance, for three different receiver heights.

It even appears that spectral measurements made on an aircraft during an overflight are not free from perturbations produced by ground reflections, as illustrated in Fig. 4, which pertains to jet noise spectra measured during the passage of a "flying bedstead" equipped with an experimental turbojet.

It is difficult to correct for such perturbations since it is almost impossible to know the momentary acoustic properties of the ground. Furthermore, these characteristics change with season, so that it is even impossible to obtain a satisfactory repeat of the same measurement in the course of time. An a fortiori comparison of measurements made on the same turbojet above two grounds of different natures is completely illusory.

To obviate these latter drawbacks and with the aim of standardizing the measurement, I.S.O.* has recently proposed [1] that the measurement of sound fields of turbojets be made above a hard surface (concrete or similar) which at least gives the advantage of ensuring fixed acoustic characteristics for the ground.

To carry out its studies of turbojet noise, in 1967 SNECMA established a test facility at Istres that allows making acoustic measurements on turbojets in conformity with the I.S.O. recommendation.

This installation includes a static-test stand mounted on a thrust-balance capable of handling a 30-ton thrust from the jet. The test area, entirely of concrete, allows making polar measurements of the sound field along a semicircle of 60-meters radius with a telecommanded cart carrying the microphones.

As an example, Fig. 3 shows the spectra of an ATAR turbojet as measured on this installation. The interferences between direct and reflected signals show up clearly.

Since the concrete surface of this installation acted as a perfect reflector for the significant wavelengths in the turbojet spectra, it was thus possible to go beyond the goal recommended by I.S.O. in seeking a method for

* International Standards Organization

correcting the spectra to allow deducing the free-field spectra from measurements made with the presence of the reflector.

3. THEORETICAL STUDY

3.1 Hypotheses

Before beginning the theoretical analysis of the problem a number of simplifying hypotheses must be enunciated.

We shall first suppose that the receiver location in the sound field is remote from the noise source represented by the jet. This condition is satisfied if the source-receiver separation is a multiple both of the wavelength of the sound being investigated and of the largest linear dimension of the source. The spectra emitted then preserve their shape during propagation since each of the components of the spectrum obeys the inverse square law with distance to the source, on condition that atmospheric absorption (which is especially marked at high frequencies) is neglected.

We shall also assume that the jet produces stationary random noise satisfying the ergodic hypothesis. The atmosphere in which the noise propagates is taken to be stationary, isothermal and homogeneous, and, finally, it is supposed that reflection of the noise from the surface (assumed to be a perfect reflector) is specular, which leads to adopting the concept of an image source, symmetrically located with respect to the reflector from the source. Under these conditions the reflected noise and the noise arriving directly at the receiver are coherent.

3.2 Establishment of Fundamental Relationships

The following theoretical analysis is based on the major lines of the analysis developed by Howes [2].

The geometry of the problem is illustrated in Fig. 6. Let p(t) and $p'(t-\tau)$ be random functions representing the noise propagating via the direct path r and the reflected path r', respectively, with τ being the delay between the two signals:

$$\tau = \frac{r' - r}{c} = \frac{\Delta r}{c}$$

The resultant signal at the receiver level can be written

$$P(t, \tau) = p(t) + p'(t-\tau) \tag{1}$$

from which the expression for its mean-square value, independent of t, is:

$$\overline{[P(\tau)]^2} = \overline{[p(t)]^2} + \overline{[p'(t-\tau)]^2} + 2\,\overline{p(t).p'(t-\tau)} \tag{2}$$

As a consequence of the different paths traversed by the signals p(t) and $p'(t - \tau)$, one can set down (taking into account the spherical divergence of the waves):

$$\overline{p(t).p'(t-\tau)} = \frac{r}{r'}\overline{p(t).p(t-\tau)}$$

where $p(t - \tau)$ is an auxiliary function corresponding to the noise propagated along r but emitted at time $(t - \tau)$. It is thus possible to bring out in (2) the autocorrelation function of p(t), a function of the sole variable τ:

$$\Gamma(\tau) = \overline{p(t).p(t-\tau)} \tag{3}$$

The ratio of the resultant mean-square pressure to the mean-square pressure in the free-field is thus written, noting that

$$\overline{[p'(t-\tau)]^2}/\overline{[p(t)]^2} = (r/r')^2 :$$

$$R = \frac{\overline{[P(\tau)]^2}}{\overline{[p(t)]^2}} = 1 + \left(\frac{r}{r'}\right)^2 + 2\left(\frac{r}{r'}\right)\frac{\Gamma(\tau)}{\overline{[p(t)]^2}} \tag{4}$$

It is shown [3] that the autocorrelation $\Gamma(\tau)$ of the real function p(t) is the Fourier transform of the spectral density w(f) or p(t):

$$\Gamma(\tau) = 2\int_0^\infty w(f)\cos 2\pi f\tau \, df \qquad \text{(Bochner-Kintchine Theorem)} \tag{5}$$

As a result, we have

$$[p(t)]^2 = \Gamma(0) = 2\int_0^\infty w(f)\, df \tag{6}$$

Since the sound-pressure spectra of jets are relatively flat, we shall take the noise in each frequency band to be white noise; it therefore has a spectral density that is constant and equal to w_0, irrespective of the mode of analysis selected.

For a frequency band with cut-off frequencies f_a and f_b (ideal filter), expression (4) is thus written:

$$R = 1 + \left(\frac{r}{r'}\right)^2 + 2\left(\frac{r}{r'}\right)\frac{1}{2\pi\tau(f_b - f_a)}[\sin 2\pi f_b\tau - \sin 2\pi f_a\tau]$$

or

$$R = 1 + \left(\frac{r}{r'}\right)^2 + 2\left(\frac{r}{r'}\right)\left[\frac{\sin\pi\tau(f_b - f_a)}{\pi\tau(f_b - f_a)}\cos\pi\tau(f_a - f_b)\right] \tag{7}$$

On setting

$$\left.\begin{aligned} \alpha &= 2\pi\frac{\Delta f}{2f_1} \\ \beta &= 2\pi\sqrt{1 + \left(\frac{\Delta f}{2f_1}\right)^2} \end{aligned}\right\} \quad \text{parameters determining the mode of analysis selected}$$

$$Z = \frac{r'}{r} = \sqrt{\frac{r_1^2 + (h + h')^2}{r_1^2 + (h - h')^2}} \qquad \text{geometrical parameter}$$

and expressing the ratio R in decibels, the resulting correction factor for reflections from a perfectly-conducting plane becomes:

$$\Delta N\,(\mathrm{dB}) = 10\log_{10} R = 10\log_{10}\left[1 + \frac{1}{Z^2} + \frac{2}{Z}\left(\frac{\sin\alpha\frac{\Delta r}{\lambda_1}}{\alpha\frac{\Delta r}{\lambda_1}}\cos\beta\frac{\Delta r}{\lambda_1}\right)\right] \tag{8}$$

Two important limiting cases should be noted:

$\Delta r/\lambda_1 = 0$ corresponding to $\Delta r = 0$ or $Z = 1$:

The two signals are added and a 6 dB increase in level results.

$\lambda = 0$ or $\beta = 2\pi$:

This is the case of interference of two signals emitted from the same "monochromatic" source with a delay τ between them. In this particular case, expression (5) takes the familiar form:

$$\Delta N = 10\log_{10}\left[1 + \frac{1}{Z^2} - \frac{2}{Z}\cos 2\pi\frac{\Delta r}{\lambda_1}\right] \qquad (9)$$

Figs. 7 and 8 show, for the geometrical factors characterized by the parameter Z, the variations of ΔN as a function of the parameter $\Delta r/\lambda$ for two current methods of analysis (analysis by 1/3-octaves and analysis by octaves).

The graph of Fig. 9 permits rapid determination of the geometric parameter Z. Using this parameter the geometry of a case of reflection can be characterised in an overall way. The correction factors given in Figs. 7 and 8 have been calculated for Z = 1,2 and 4 but it should be noted that Z, which is equal to the ratio of the distance traversed by the reflected wave to that traversed by the direct wave, takes on a value close to unity in most practical cases.

4. EXPERIMENTAL STUDY

4.1 Arrangement and Experimental Method

To carry out the experimental verification of the hypotheses and calculations set forth in the last Section we deemed it necessary to set up a test arrangement that would permit simultaneous measurement of the spectra of a jet in the free-field and in the presence of a reflecting surface. This requirement obviously excluded the possibility of a study made directly on a turbojet.

The experimental study was th[illegible]ied out on a jet mock-up with a convergent nozzle. The test arrangement, shown in Fig. 10, was set up in the anechoic chamber of the Engine Test Center at SACLAY. In addition to satisying thereby the free-field conditions this brought with it other advantages, namely, temporal stability of jet exhaust and a quiet and isothermal ambient atmosphere.

The nozzle, 76 mm in diameter and mounted on a test-stand, was supplied under constant operational conditions (ejection velocity $\approx$ 500 m/s).

The measuring arrangement, shown in Fig. 10, could be rotated around a vertical axis through the center of ejection of the nozzle and included:

- a variable-height microphone support arm
- a reflecting plane of metal plates arranged on a framework suspended from rotatable arms by small-diameter rods with threaded ends to permit regulation of the height of the plane with respect to the nozzle.

Thus by rotating the arms the sound field of the jet could be examined at azimuths of 30° - 120° with respect to the jet axis.

The acoustic measurements were made using a standard recording system and the spectra were analyzed by third-octaves and octaves in the frequency region 200 - 40,000 Hz.

The operational method was to record the sound-pressure spectra of the jet in the free-field and in the presence of the reflecting plane for each experimental geometry characterized by the parameters h, h', r_1 and θ .

Since these two measurements could not be made simultaneously, preliminary tests were made which verified that the spectra were completely stationary and reproducible.

4.2 Some Experimental Results

Many geometries corresponding to different values of the parameter Z have been studied to date. Nevertheless, in view of the considerable number of parameters on which the problem depends and special problems tied to specific geiometries, the scope of the tests is not yet covered in its entirety. We shall restrict ourselves here to giving some results relating to a Z very close to unity. This limiting value, which corresponds to $r'/r \simeq 1$, covers most practical cases of measurements in the far-field of a turbojet (static tests or measurements on aircraft in flight).

The values given in Fig. 11, measured in the direction of maximum emission of noise from the jet, correspond to identical heights for microphone and jet axis (mean height of source) and three different distances between 5 and 6 meters (analysis by third-octaves). These different geometries can be considered to be representative of measurements in the far-field of the sound from a jet under static-test conditions.

The results corresponding to geometries more nearly approximating overflight are illustrated in Fig. 12, as deduced from measurements made at an azimuth of 90° (analysis by third-octaves).

To complete this brief survey of the experimental investigations, Fig. 13 shows the results of analyses by octaves in the direction of maximum sound emission for different experimental geometries.

It is seen that on the whole the agreement between theory and experiment is satisfactory, despite some dispersion of the measured points -- which should not be surprising. In fact, it is clear that the jet is far from being equivalent to a point source and that rigorous determination of distances is always critical. Also, it should be pointed out that certain anomalies observed for specific test geometries should be made the object of complementary tests.

5. EXAMPLES OF PRACTICAL APPLICATION

In the last section of this account we shall present some examples of the practical application of the studies just discussed.

The first application concerns the correction of the measurements made on the Istres installation described at the beginning of this article, with the aim of establishing the free-field characteristics of the noise emitted by jets.

Fig. 14 thus shows sound-pressure spectra from an ATAR turbojet that have been corrected using the results previously established. For purposes of comparison we have shown on the figure the free-field spectra calculated using the noise prediction method established by SNECMA [4]. The two examples considered demonstrate that it is possible to restore the trend of the free-field spectra with a rather good approximation.

A second sort of application concerns problems of predicting the noise spectra of jets. As an example we have compared (Fig. 15) spectra measured on the same installation and the calculated spectra, this time applying the correction terms resulting from reflections to the free-field spectra.

It is seen that the agreement between the predicted curves and the measurements is quite satisfactory although the first null is clearly less important than the value calculated for it.

As a final example of application, Fig. 16 shows once again the spectra of

Fig. 4 measured during overflight and the corresponding calculated spectra. Since the ground characteristics were unknown we hypothesized a perfectly-reflecting ground to establish the calculated spectra, a hypothesis that certainly does not correspond to reality. Although the observed agreement between the measurements and calculations could be fortuitous, it serves to stress the precautions one should take when making acoustic measurements on aircraft in flight.

6. CONCLUSIONS

To conclude this account, in which we have given a brief survey of the theoretical and experimental problems of reflections, more specifically focussed on the acoustic spectra of jet noise, we should add some remarks.

To begin, for certain special cases of the problem that relate to limiting geometries the results do not match the quality of those we have discussed. This concerns especially the case of grazing incidence, when jet and microphone are very close to the reflecting plane.

The results likewise appear to be impaired when the jet is near the surface and the microphone is very far from the jet.

In these latter cases it is probable that the hypothesis of a point source can no longer be maintained and that a distribution of sources must be taken into account in the problem. A theoretical and experimental study of these particular points is in process.

A third factor that bears on the results is essentially the existing experimental conditions, namely the influence of a non-homogeneous atmosphere, wind, surface roughness and inaccuracy in measuring the distances. These perturbations lead to dispersion of the results, which is particularly pronounced near the extremities of the correction curves and is more marked the narrower the band of the analysis.

Notwithstanding these remarks, in most practical cases the application of the correction factors we have defined will permit a more realistic approach to the free-field acoustic characteristics of jets.

APPENDIX

Nomenclature:

c	velocity of sound
f	frequency (Hz)
f_a, f_b	cut-off frequencies of a band of width Δf
Δf	bandwidth
f_i	center frequency of a band $f_i = \sqrt{f_a f_b}$
h	height of source above reflecting plane
h'	height of receiver above reflecting plane
N	level of sound-pressure in dB
p, p'	sound pressures
r	source-receiver distance
r_1	projection of direct ray on reflecting plane
r'	path length of reflected signal
Δr	path difference between direct- and reflected- signals
R	ratio between the mean square of the resultant signal and the direct signal
	$10 \log_{10} R = \Delta N$: value of R in dB
t	time
$w(f)$	spectral density
Z	geometrical parameter $Z = r'/r$
α	parameter defining the mode of spectral analysis $= 2\pi \Delta f / 2f_1$
β	parameter defining mode of spectral analysis $= 2\pi \sqrt{1 + (\Delta f/2f_1)^2}$
θ	angle between axis of jet and direction of sound emission
$\Gamma(\tau)$	autocorrelation function of $p(t)$
τ	delay

λ	wavelength
λ_1	wavelength corresponding to the center frequency of a band
$\overline{(\quad)}$	time-average of a quantity
$\overline{(\quad)^2}$	mean-square value of a quantity

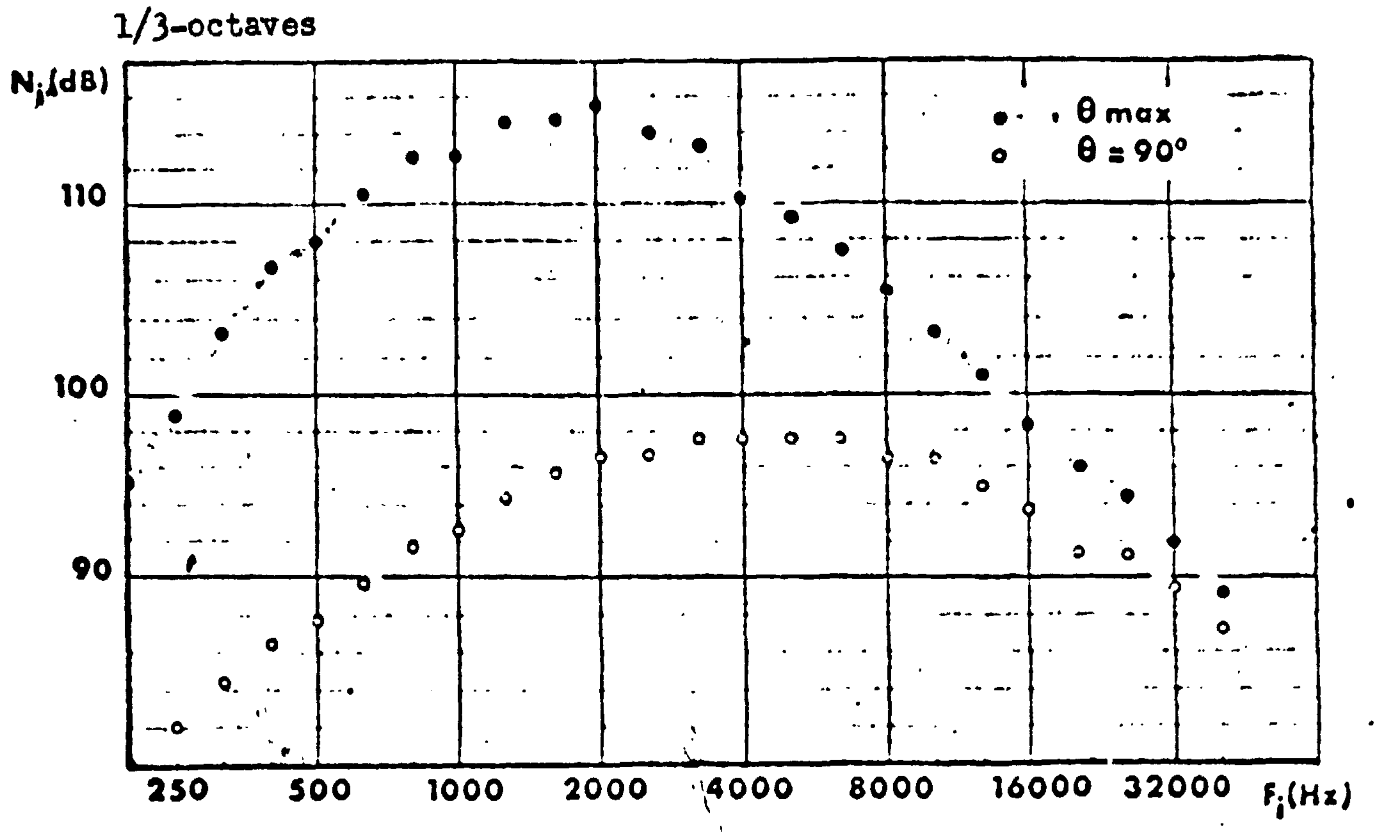
LITERATURE REFERENCES

(1) I.S.O. Recommendation R 507: A method of representing aircraft noise in the vicinity of an airport (October 1966)

(2) W. L. Howes, Ground reflection of jet noise. NASA TR R-35 (1959)

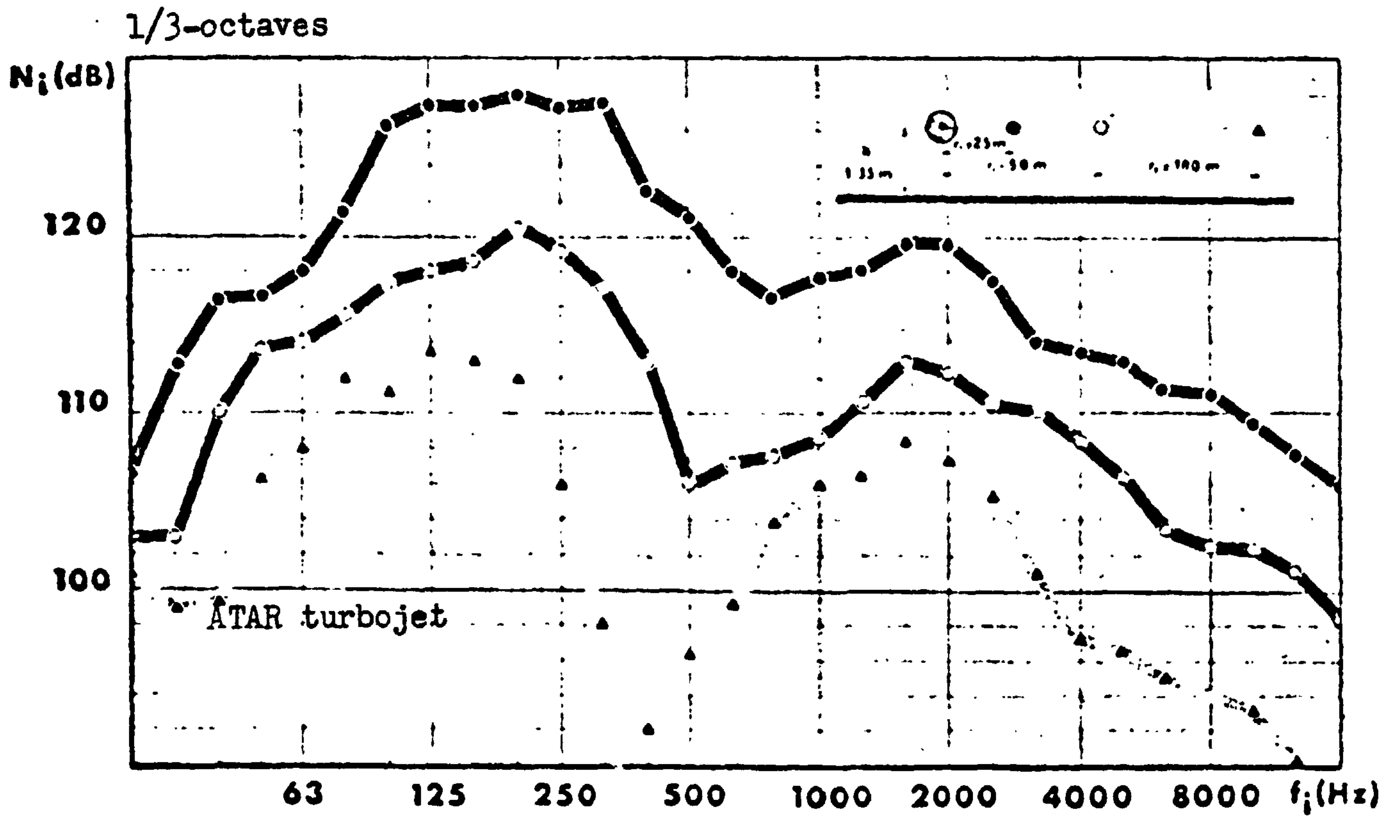
(3) J. Stern, Practical methods for studying random functions, Ed: DUNOD (Paris, 1967).

(4) Method of predicting turbojet engine noise. Document No. 3497/YLLA SNECMA (October, 1967).



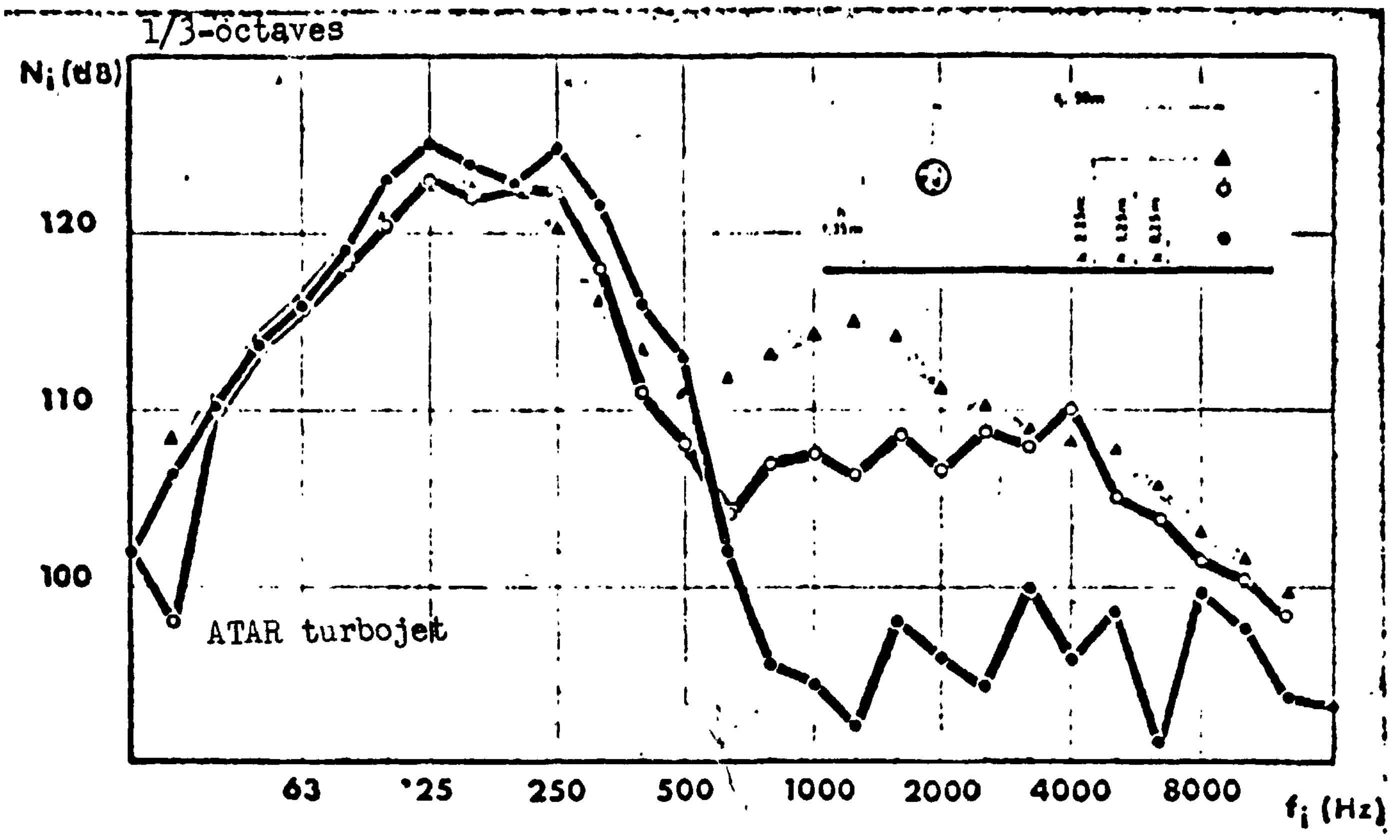
Jet spectra, free-field measurements
(Mockup)

Fig. 1

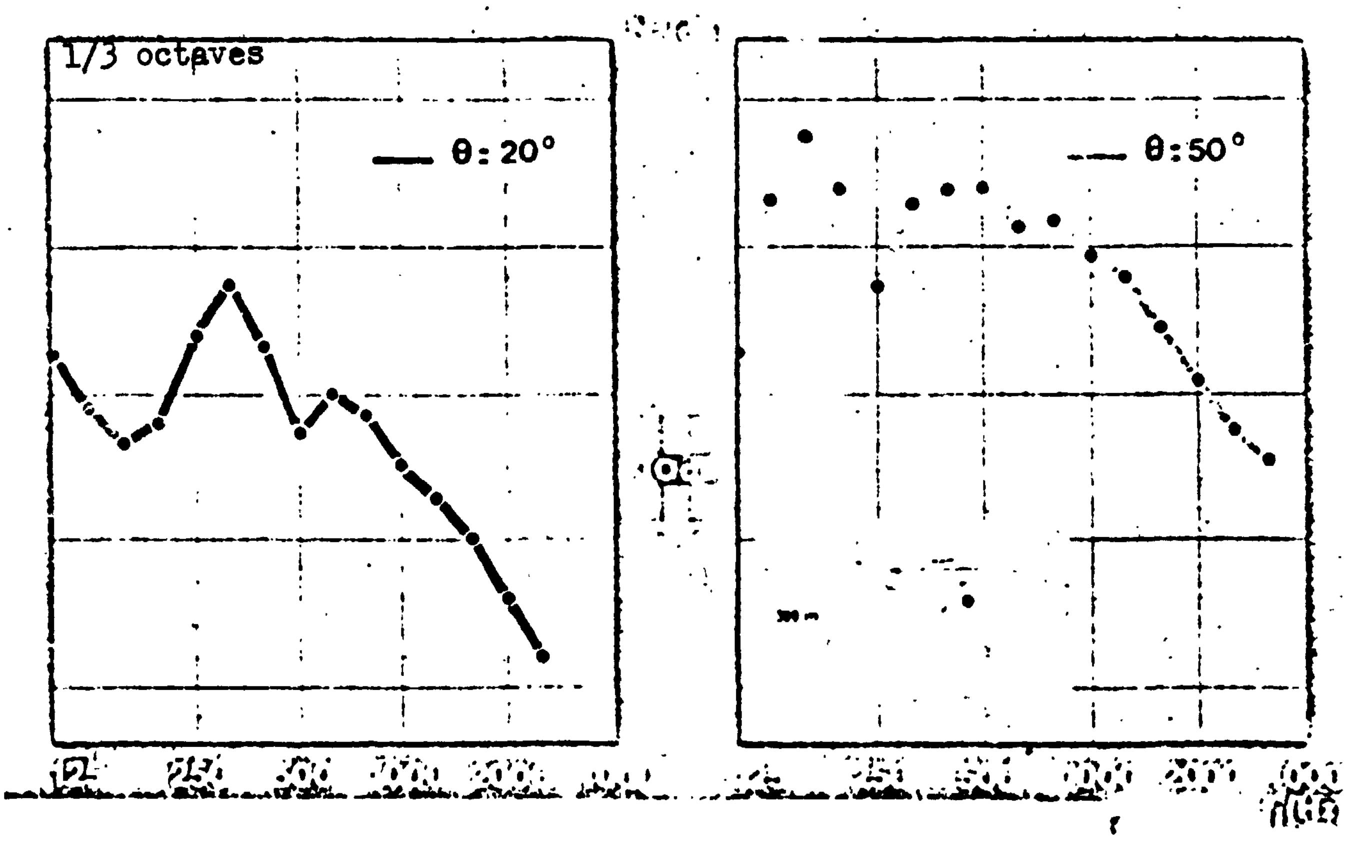


Jet spectra measured in the presence of a grassy ground
(distance variable)

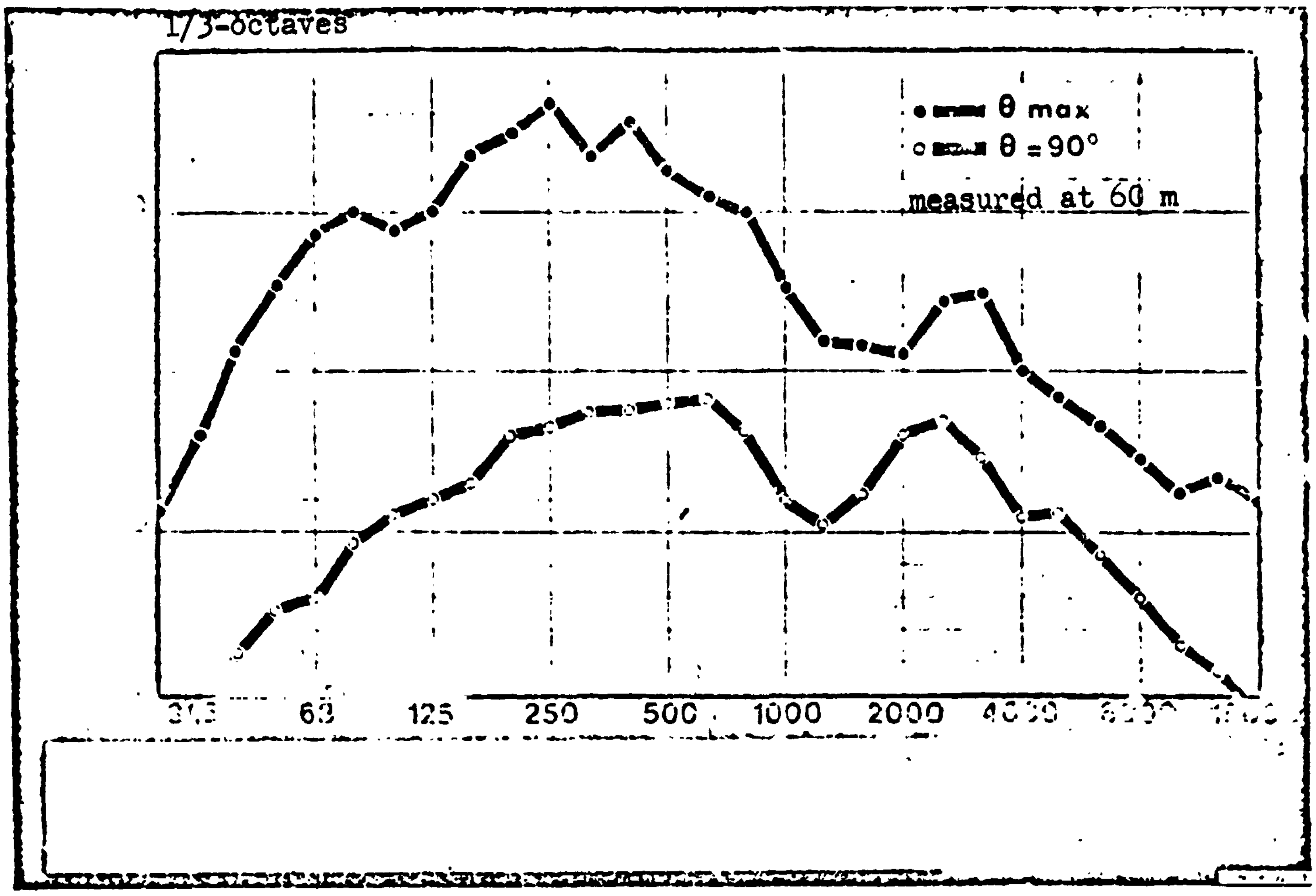
Fig. 2



Jet spectra measured in the presence of a grassy ground (height variable) Fig. 3



Jet spectra measured during an overflight Fig. 4



Jet spectra measured in the presence of a reflecting ground (ATAR) Fig. 5

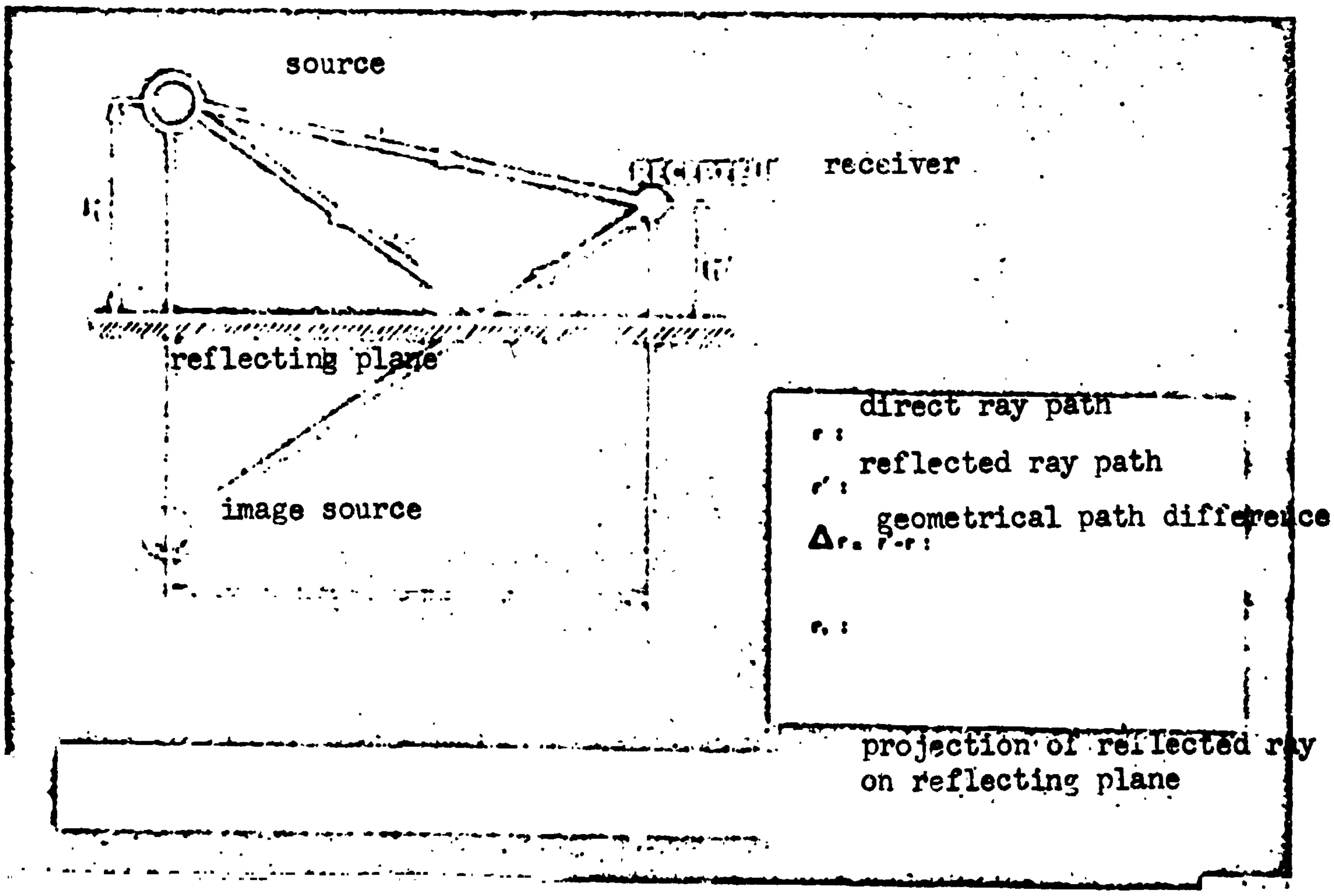
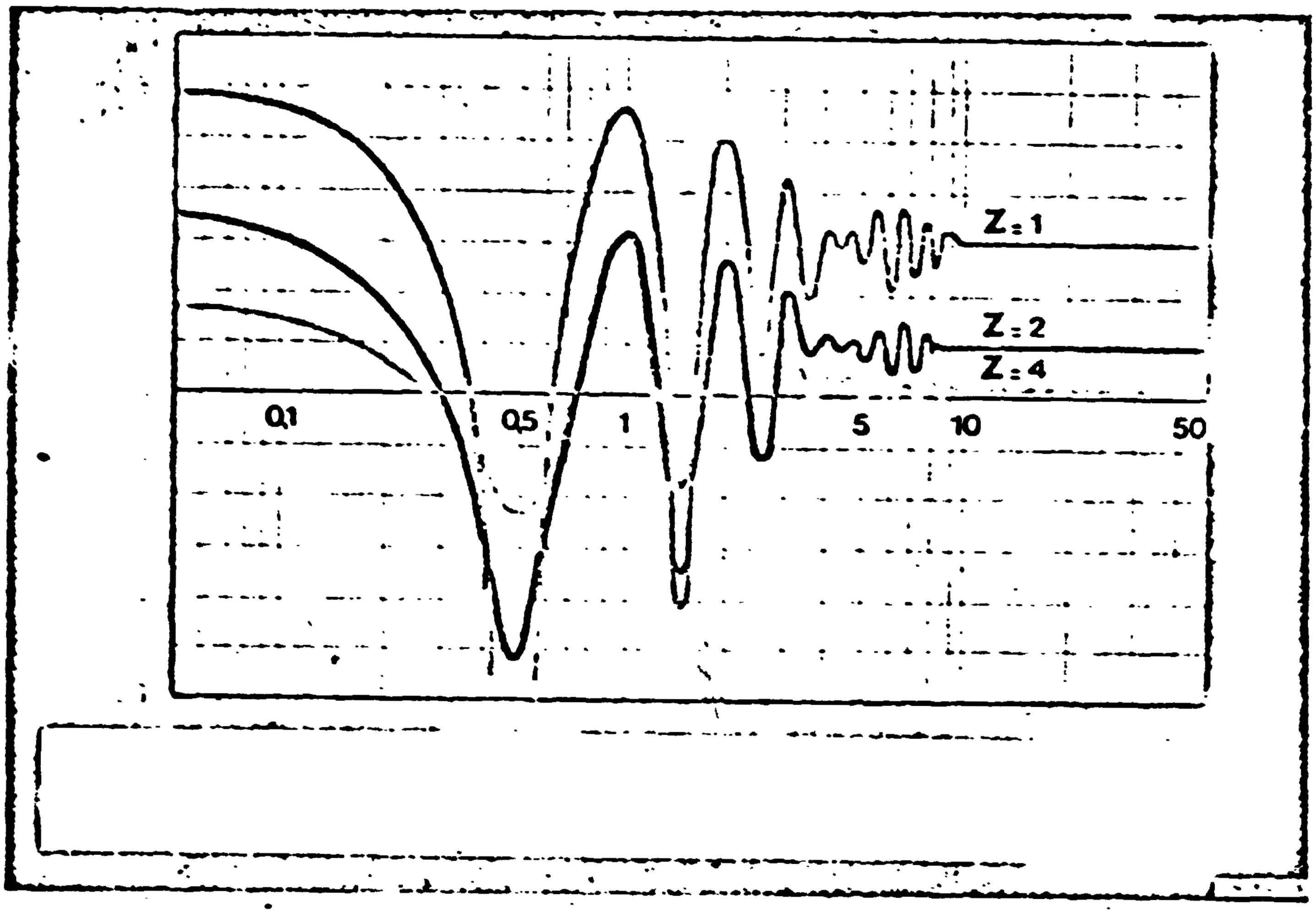
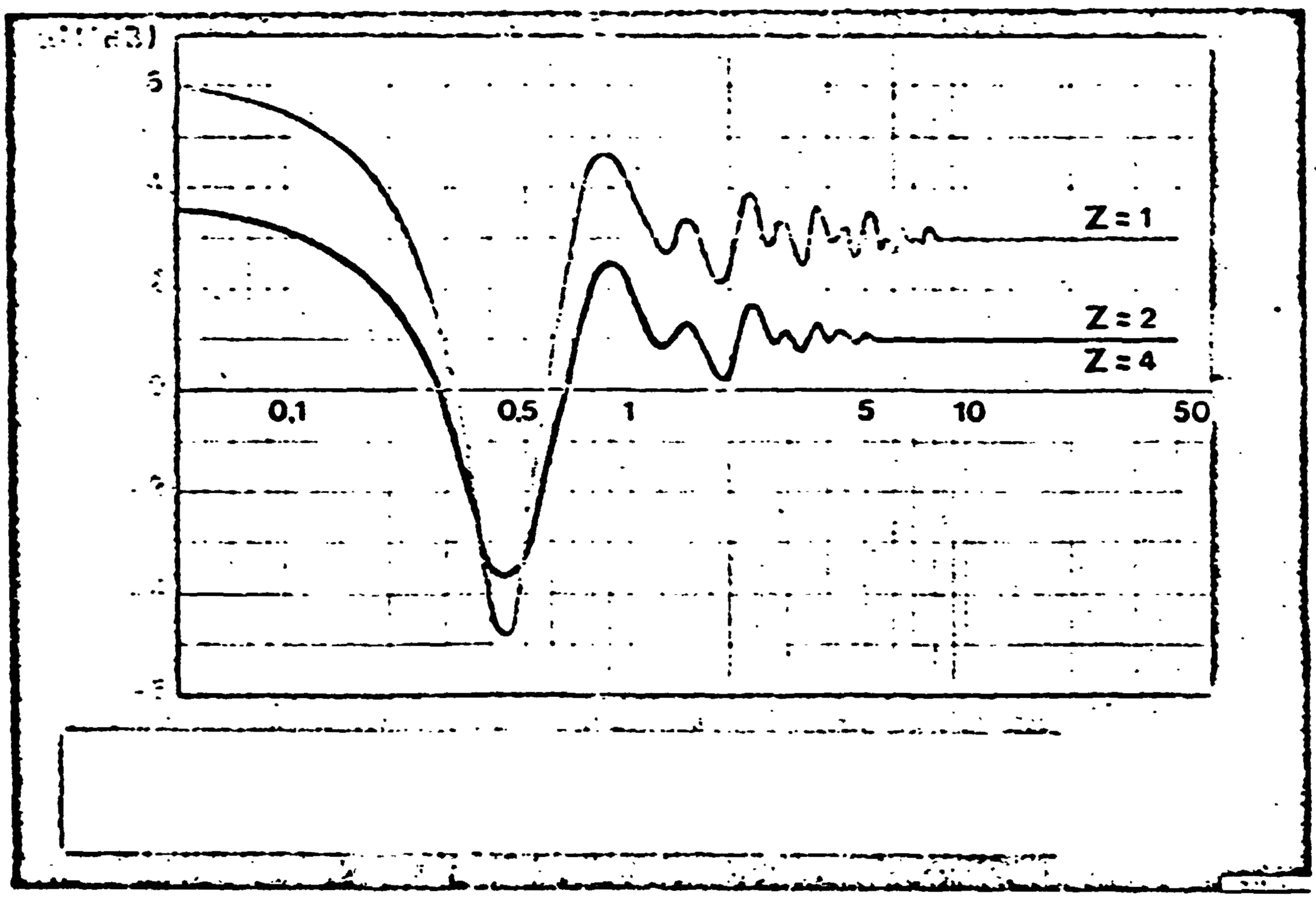


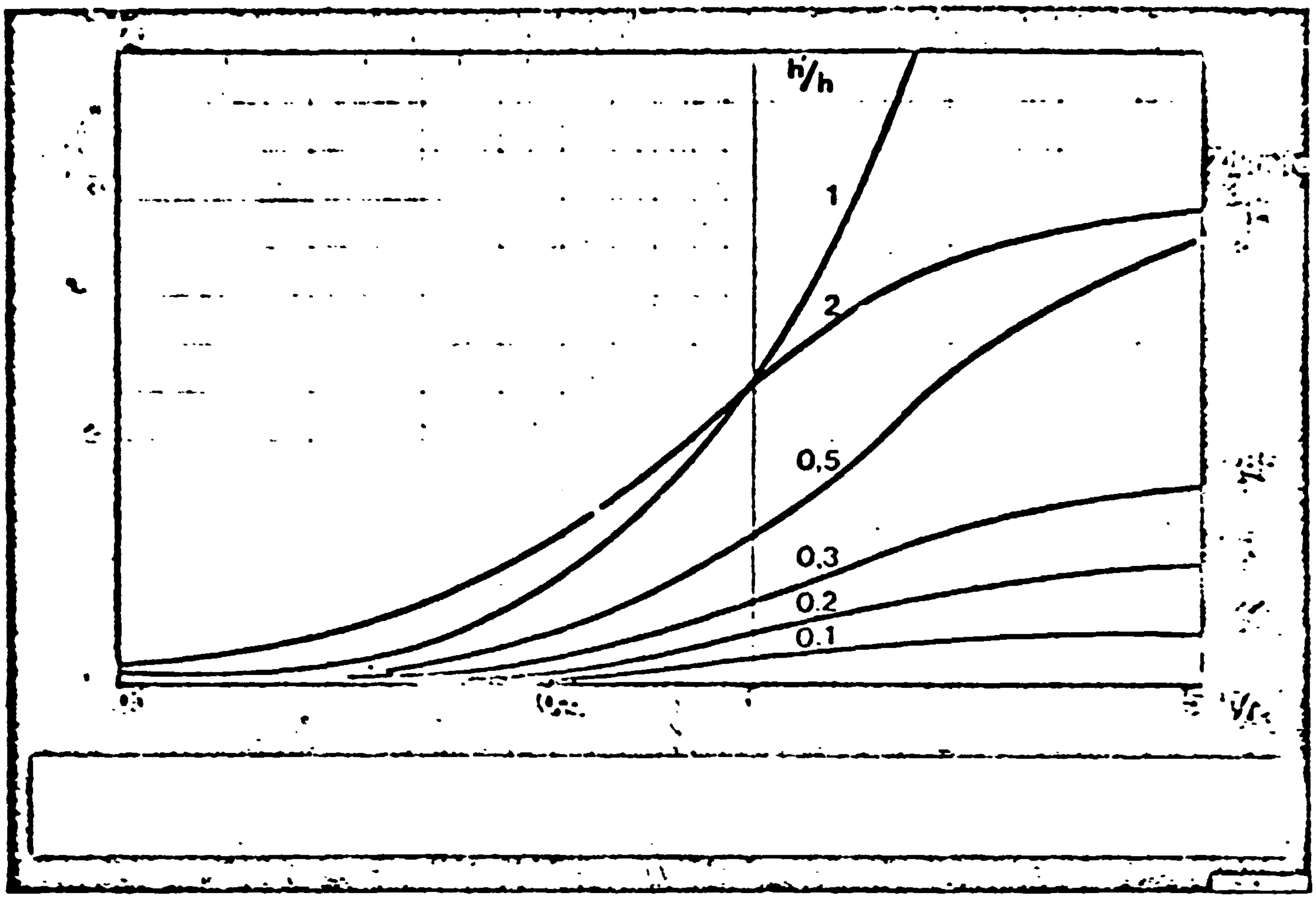
Diagram of problem Fig. 6



Correction factors with a perfect reflector (analysis by 1/3-octaves). Fig. 7

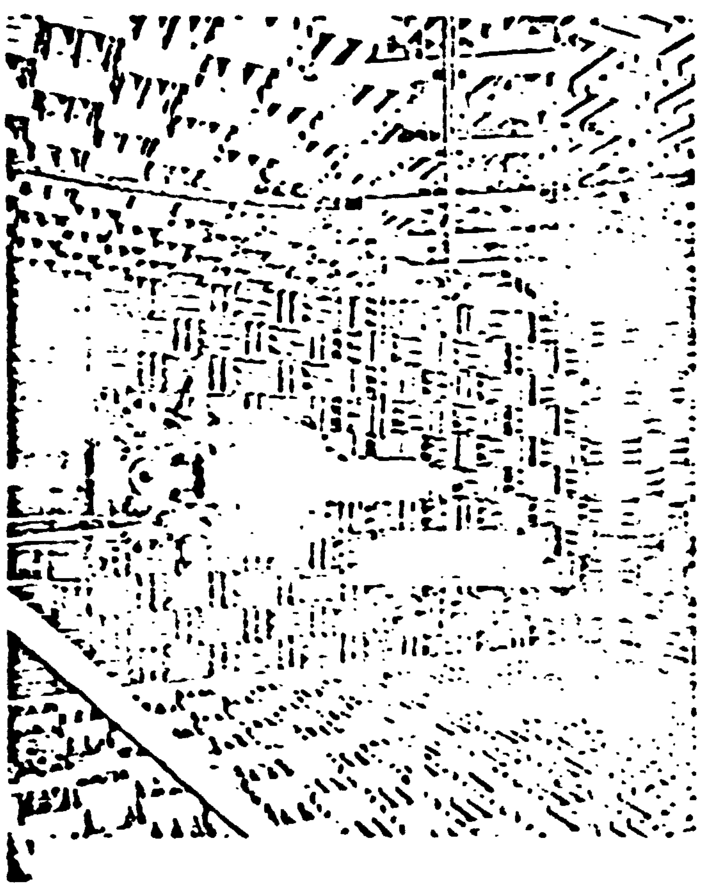


Correction factors with a perfect reflector (analysis by octaves) Fig. 8



Practical determination of the geometrical parameter Z

Fig. 9



Experimental arrangement in the CEP anechoic chamber

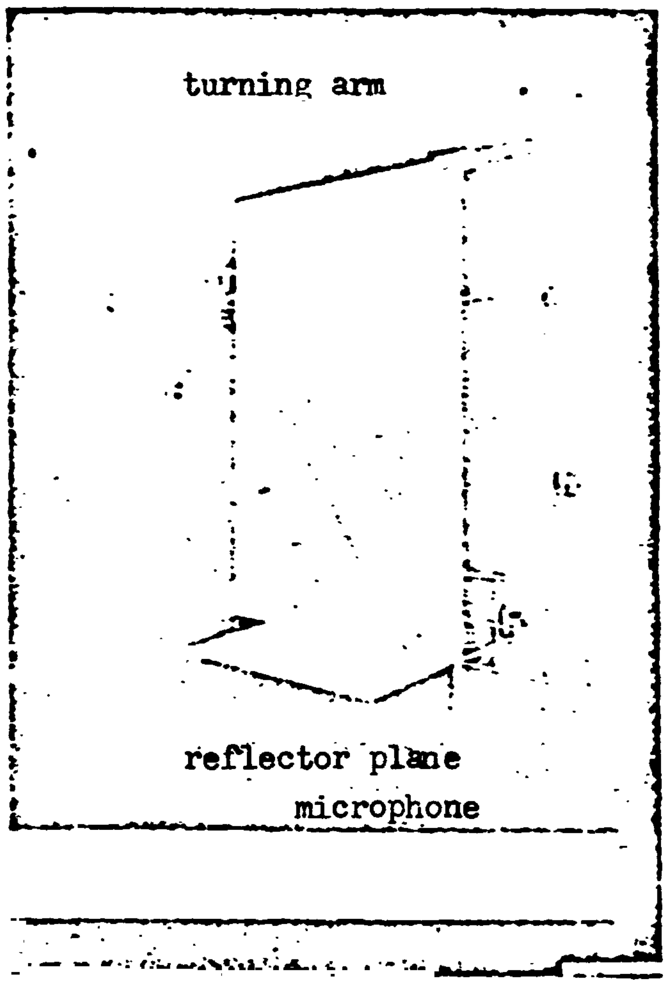
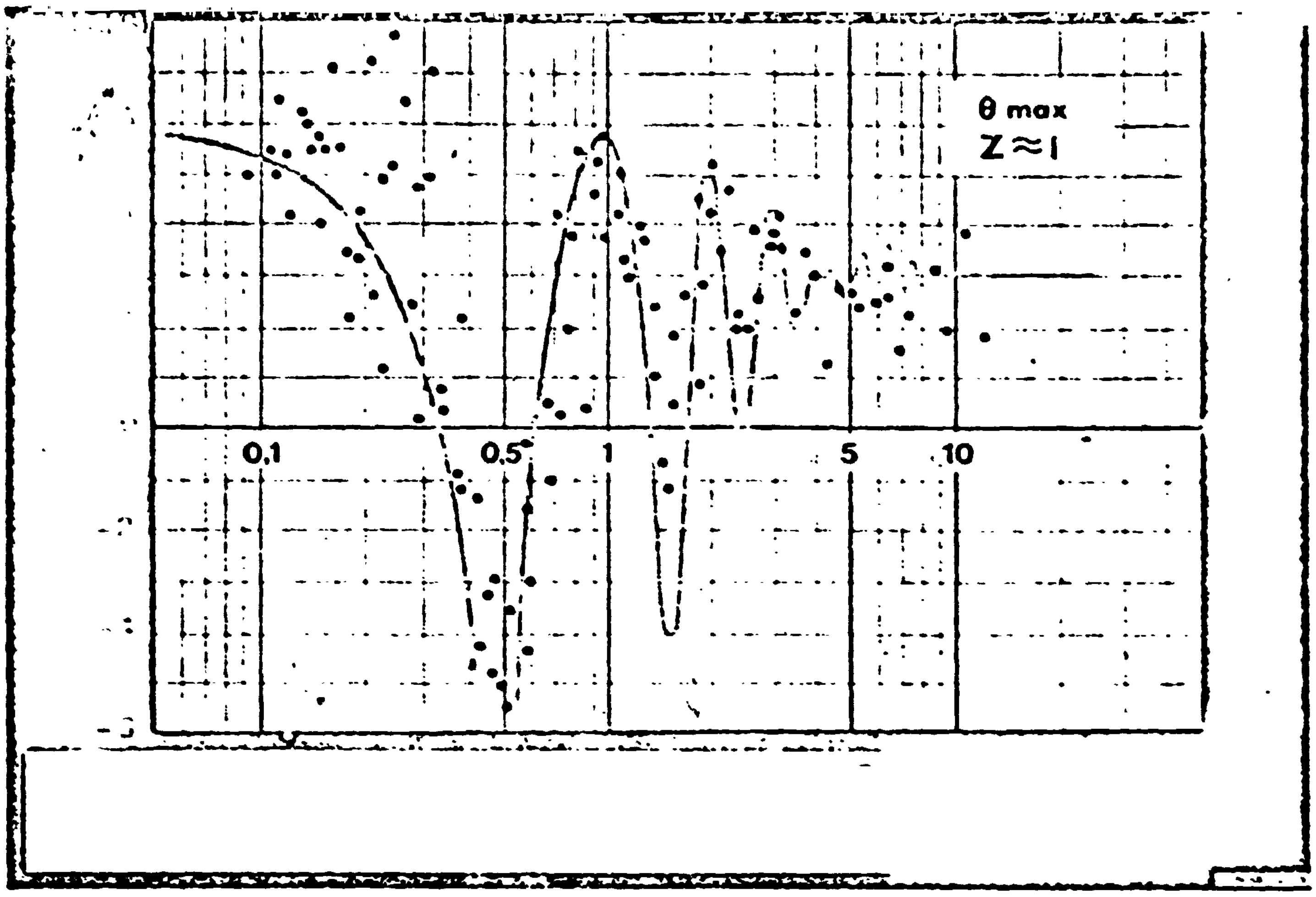
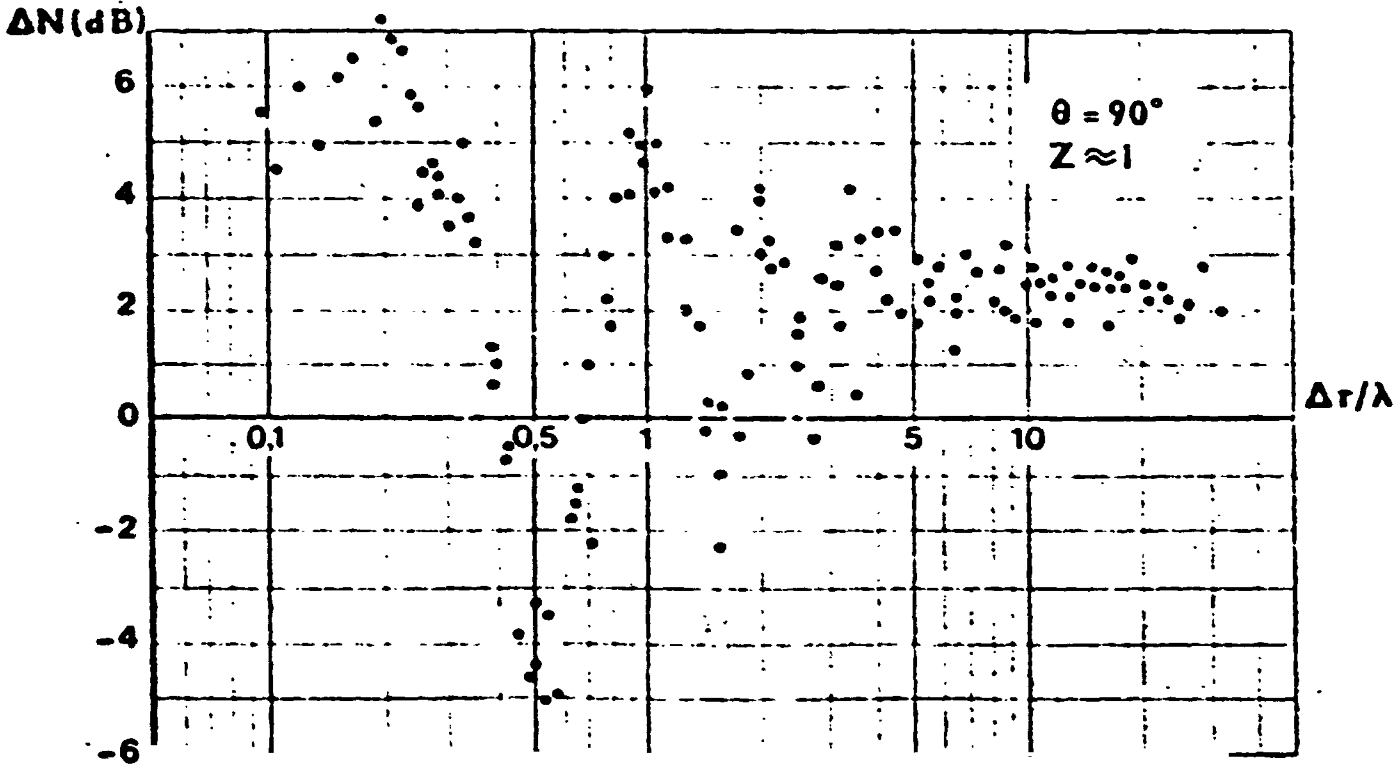


Fig. 10



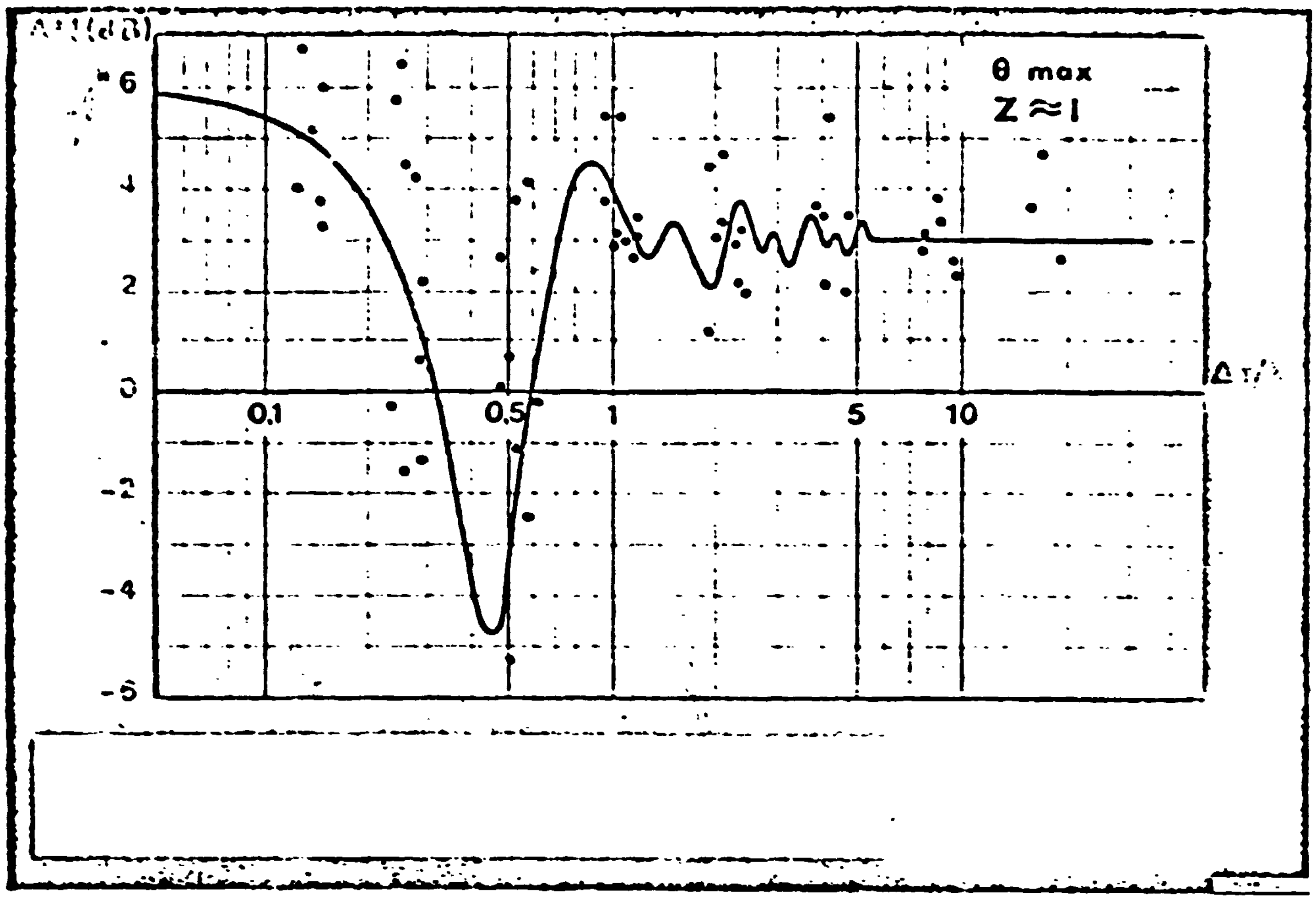
Results of measurements on mockups
(analysis by 1/3-octaves)

Fig. 11



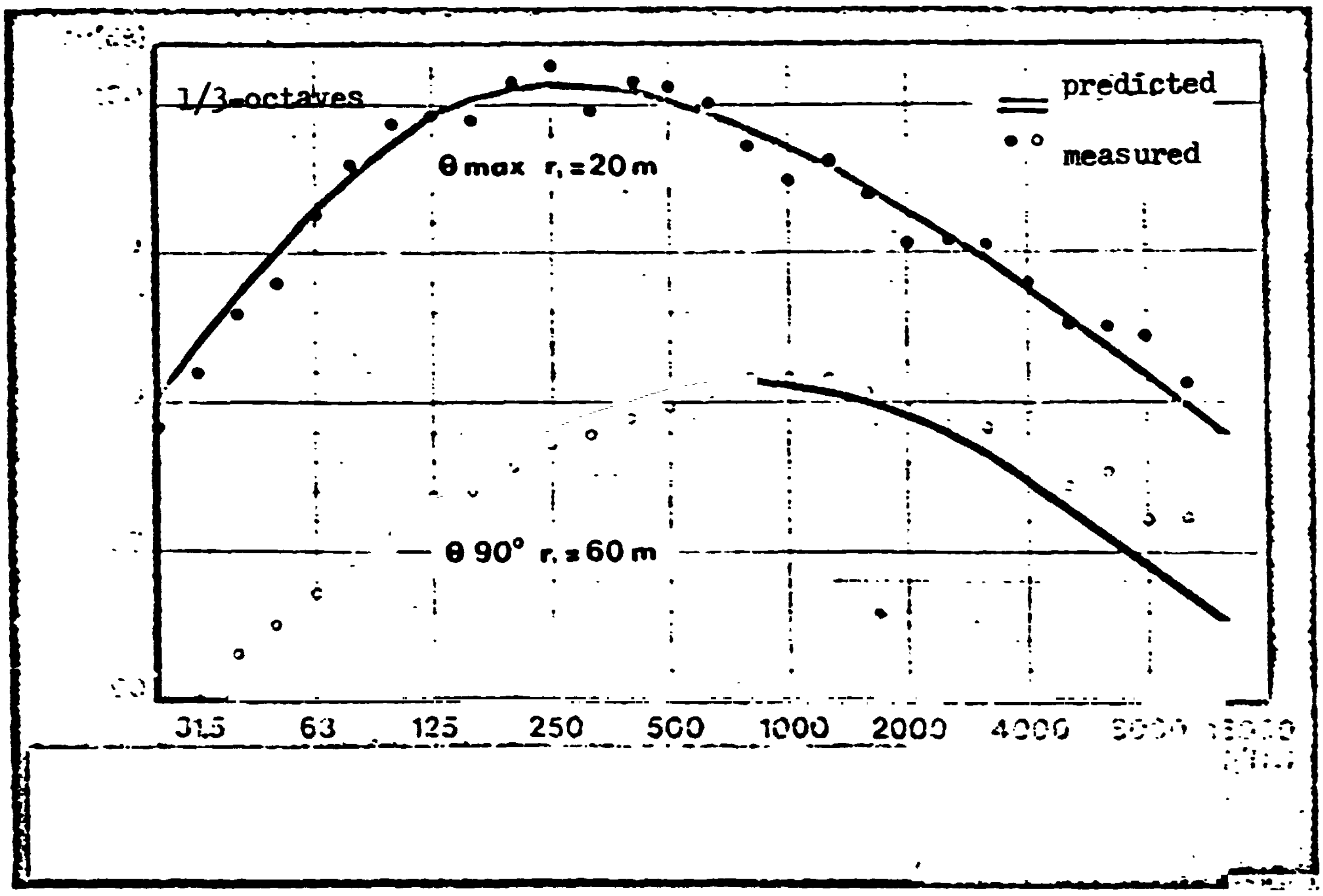
Results of measurements on mockups
(analysis by 1/3-octaves)

Fig. 12



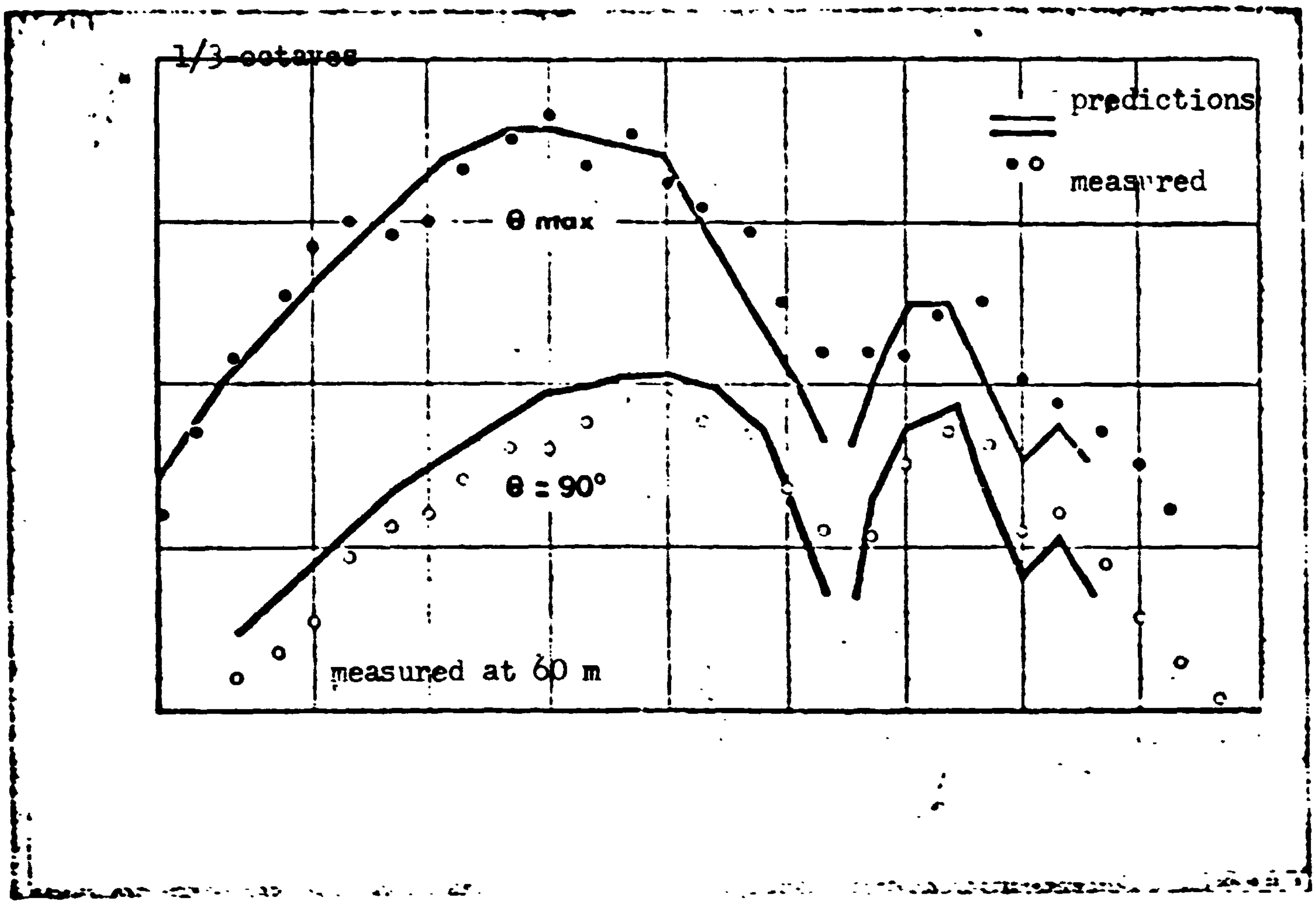
Results of measurements on mockups
(analysis by octaves)

Fig. 13

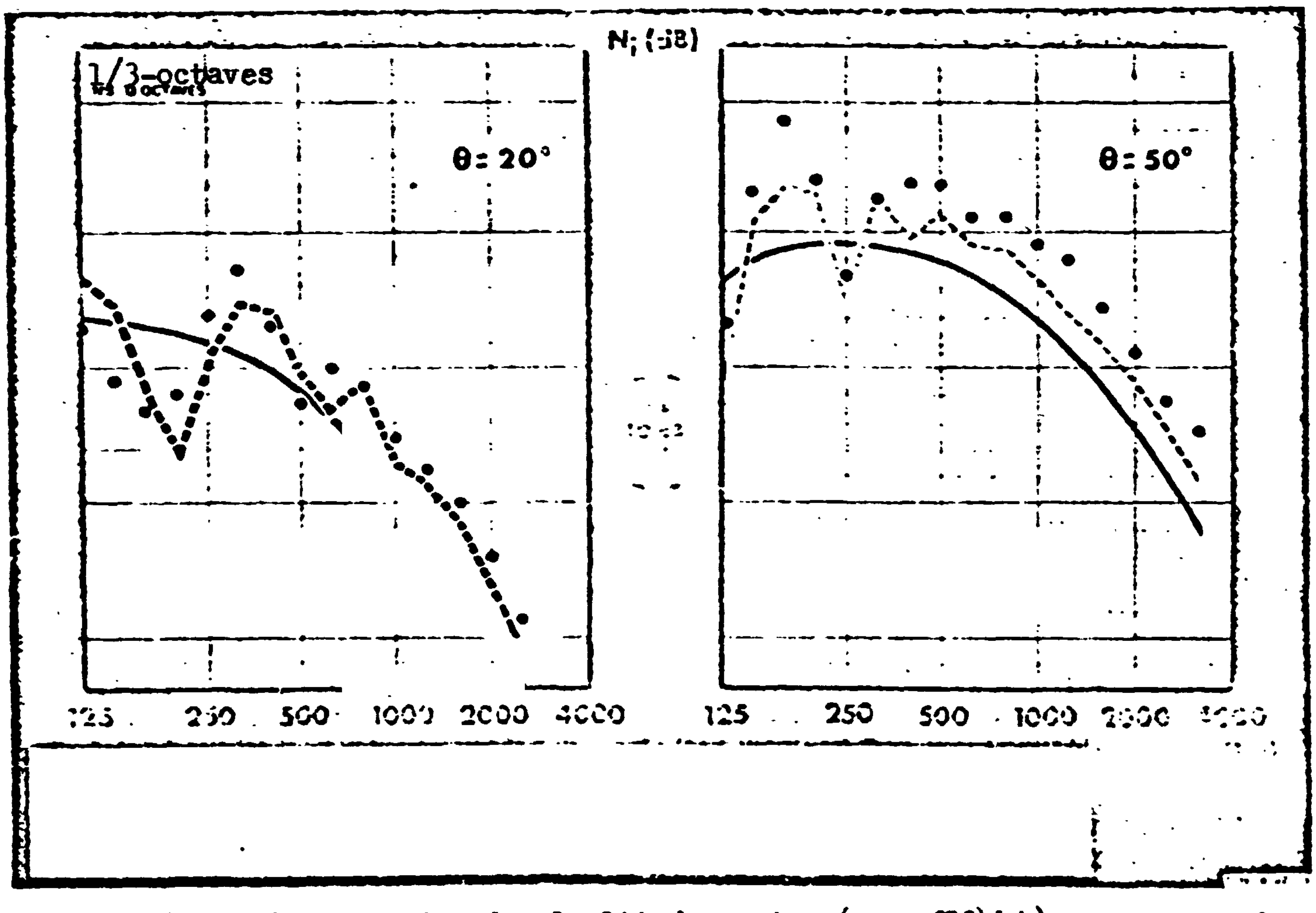


Examples of reconstitution of the free-field spectra
(ATAR static test)

Fig. 14



Comparison of measured and calculated spectra (ATAR static test) Fig. 15



Comparison of measured and calculated spectra (overflight) Fig. 16

- ● measurements
- —— free-field prediction
- - - - prediction with reflection